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The thermal deformation reducing in sheet metal at manufacturing parts by CNC cutting machines

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Abstract. In various industries for the manufacturing of parts (workpieces) from sheet metal the CNC machines for thermal cutting (laser/plasma/gas cutting) are used. During process of thermal cutting, various deformations of the metal can occur, that cause the distortion of the geometric forms and sizes of the cut parts. These distortions are caused both by the uneven distribution of temperature in the sheet, and by certain geometric characteristics of the cutting process. Geometric characteristics are determined by the set sequence (order) of cutting of figured parts, as well as by selecting the piercing points of sheet material, i.e. the places of inserting the tool into the material. Previously, the authors formulated heuristic geometric rules, that allow reducing the value of geometric deformations of parts produced by the CNC cutting machines. To comply with these rules, users of Computer-Aided Design (CAM) systems that are used to generate NC programs, have to use interactive design methods. One of these rules (so-called "Part Hardness Rule") refers to the selecting the location of points for inserting (piercing) a CNC machine tool into the material. The paper describes a model based on the use of the heat conduction equation, which makes it possible to calculate the temperature of the sheet material at each moment of cutting process. The computational experiments showed that the points, which according to the "Part Hardness Rule" can't be used for piercing, have a higher material temperature than the points that satisfy this rule. In the paper the results of the computational experiments are given. Another rule (so-called "Sheet Hardness Rule"), which also reduces the deformation of the material during thermal cutting, refers to the order of parts cutting from the sheet. A heuristic algorithm that automatically generates the order of cutting parts that satisfy the rules of "Part Hardness" and of "Sheet Hardness" is developed. Developed software allows us to abandon the interactive methods of the NC programs generation for the thermal cutting of figured parts on CNC machines.

1. Introduction

Development of NC programs for the CNC sheet cutting machine includes two main functions (procedure):

- 1) Nesting: the placement of figured parts onto plate;
- 2) The tool path routing and choosing the tool path components.

Both procedures have to execute according to some technological constraints and optimization criteria (Nesting problem [1-2], Tool path problem [3]). In this work we are discussing the second problem. The basic components of tool path are showed on Figure 1.

Usually in non-series production for the manufacturing of parts (workpieces) from sheet metal the CNC machines for thermal cutting (laser/plasma/gas cutting) are used. During process of thermal cutting, various deformations of the metal can occur, that cause the distortion of the geometric forms and sizes of the cut parts. Figure 2 shows an example of distortion of the geometric forms and sizes of the long rectangular plate.



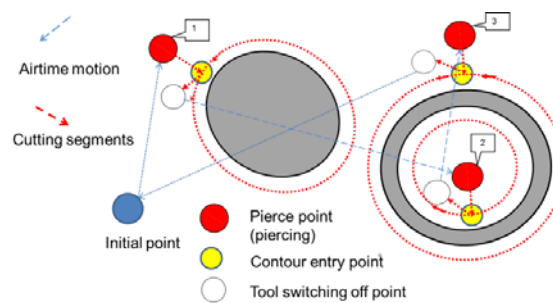


Figure 1. Basic components of tool path



Figure 2. An example of the geometric forms and sizes distortion the long rectangular plate produced by CNC flame cutting machine

The distortions are caused both by the uneven distribution of temperature in the sheet, and by certain geometric characteristics of the cutting process. Geometric characteristics are determined by the set sequence (order) of cutting of figured parts, as well as by selecting the pierce points of sheet material, i.e. the places of inserting the tool into the material. Previously, the authors formulated heuristic geometric rules, that allow reducing the value of geometric deformations of parts produced by the CNC cutting machines, are described in [4-5]. To comply with these rules, users of Computer-Aided Design (CAM) systems that are used to generate NC programs, usually use interactive design methods. One of these rules (so-called "Part Hardness Rule") has been formalize [6-7] (see Figure 3) that allowed us to develop algorithms and software for optimizing of the tool path, taking into account this rule.

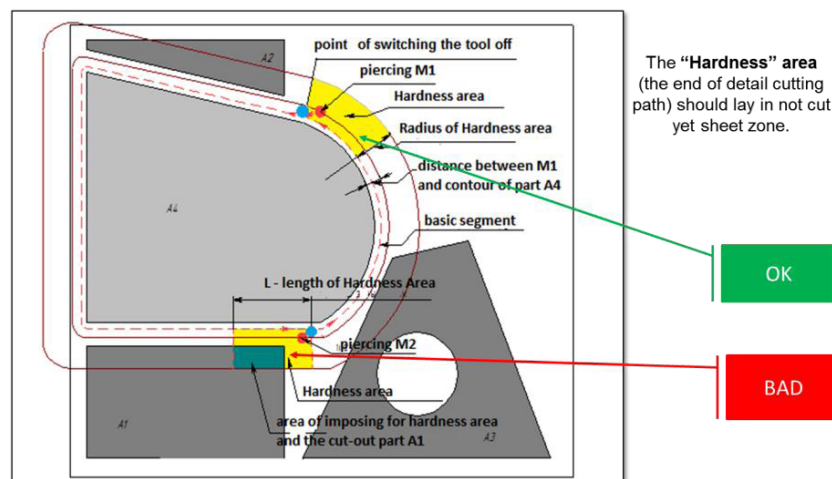


Figure 3. Illustration of „The Part Hardness Rule”

In [8] next Hypothesis is formulated: If the piercing and the zone of the completion cutting (a Hardness area) are satisfies the Part Hardness Rule then the temperature of the material in the Hardness area is lower than at using of the bad piercing. To test the hypothesis, the special software has been developed that makes it possible to calculate the temperature of the sheet material at each moment of cutting process.

2. Modeling of the thermal fields calculating and computing experiments

For each contour of parts in succession we consider the problem of finding the temperature $\theta(t, x)$ (t - time moment, x - point in the region), satisfying the following conditions:

- the heat equation
$$c\rho \frac{\partial \theta}{\partial t} = k\Delta \theta + N, \quad x \in \Omega$$

- the initial condition $\theta(t_0, x) = \theta_0(x), x \in \Omega$
- the boundary condition $-k \frac{\partial \theta}{\partial n} = M(\theta - \theta_*), x \in \partial\Omega$

t lies in the interval $[t_0, t_1]$, x is a point in the region $\Omega \in R^3$.

Here, t_0 and t_1 are, respectively, the starting and ending time of contour cutting, Ω is the part of the plate left after the removal of all the regions bounded by the previous contours, $\partial\Omega$ is the boundary of region.

Here, c is the specific heat per unit mass, ρ is the density, k is the thermal conductivity, $N(t, x)$ is the density of heat source, M is the heat transfer coefficient, $\theta_0(x)$ is the current temperature field prior to cutting a given contour, θ_* is the air temperature. The density of heat sources N is as follows. Let $p = w/(\pi r^2 h)$ be the power density of the heat "ray" and $m(t)$ is the position of the heat "ray" axis at time t . Then $N(t, x) = p$ at the points lying from the line $m(t)$ at a distance smaller than r and 0 at the remaining points.

Approximation to the problem:

The process of recalculation of the temperature field $\theta(t, x)$ during contour cutting is split into small time intervals $[t_{r-1}, t_r]$ of length Δt and for the calculation of $\theta(x) = \theta(t_r, x)$ one considers the problem

$$c\rho \frac{\theta(x) - \theta_0(x)}{\Delta t} = k\Delta\theta(x) + N(x),$$

$$-k \frac{\partial \theta}{\partial n} = M(\theta - \theta_*),$$

where $\theta_0 = \theta(t_{r-1}, x)$ $N(x) = N(t_{r-1}, x)$.

The region Ω is split into tetrahedra, the functions $\theta(x), \theta_0(x), N(x)$ are piecewise linear, they are determined by their values at the knots (vertices of tetrahedra).

The solution of this problem delivers the minimum to the following functional

$$I(\theta) = \frac{1}{2\Delta t} \int_{\Omega} c\rho(\theta - \theta_0)^2 dx + \frac{1}{2} \int_{\Omega} k |\text{grad}\theta|^2 dx - \int_{\Omega} N\theta dx + \frac{1}{2} \int_{\partial\Omega} M(\theta - \theta_*)^2 dS$$

The minimum of this functional is searched by the relaxation method [9]. The choice of this method is based on the following considerations.

The radius r of the "heat ray" is small, and hence any tetrahedron of the partition must have a small size (in calculations the side length was 2 mm) and hence their number is very large. The temperature still has the original value at the knots located far from the points already visited by the "heat ray" and where the heat change could not reach by the given time instant. The relaxation method allows one to skip such knots, which reduces the running time.

Remark. To decrease the number of tetrahedra (knots) in designing the cuts of the successive contour K_i one considers not the entire plate, but rather a piece $\Omega_i \supset \Omega_{i-1}$.

A piece is supposed to be sufficiently large in order that the temperature outside Ω_i would not change by the time of completion of cutting of contour K_i . Once the cutting of the contour is complete, the tetrahedra inside the contour are thrown away, their total number becomes smaller. Next, mesh is enlarged until we reach the next piece Ω_{i+1} .

Specialized FEM-module was developed based on the above mathematical model. Using it, a number of numerical experiments were conducted with the following parameters: sheet size 1000 x 1000 mm, beam diameter 2 mm, beam power 1500 W, cutting speed 10 m/min. Figure 4 shows the difference in average temperature in the hardness area while cutting the last of eight parts in case of selecting pierce point in compliance with part hardness rule (b) and (a) in disagreement with that rule. Temperature difference is about 120 degrees.

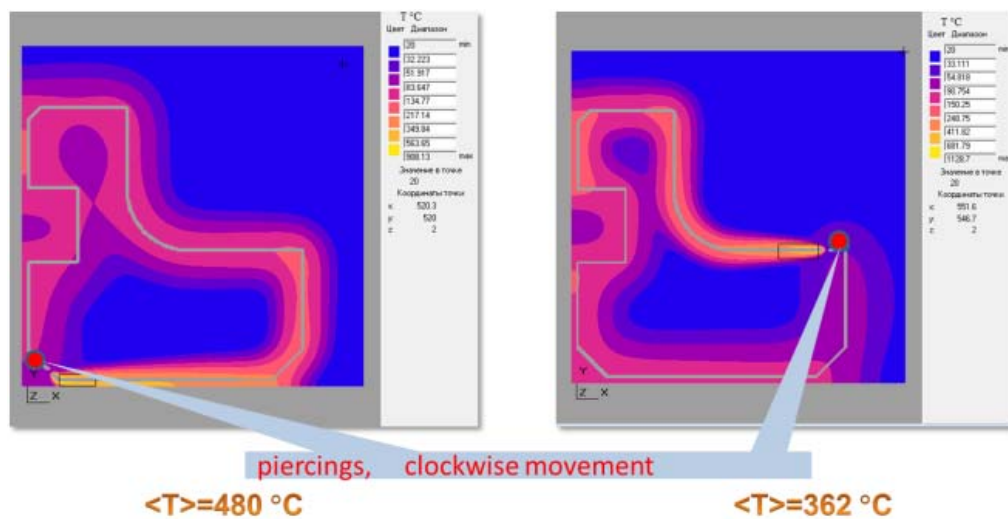


Figure 4. Thermal distribution evaluation according to the part hardness rule

3. Results and discussions

18 numerical experiments were conducted with different initial nestings and cutting orders. Obeying the part hardness rule always leads to decrease in average temperature in the part hardness area. Average temperature decrease was about 63%. Next two examples illustrate results.

An example 1

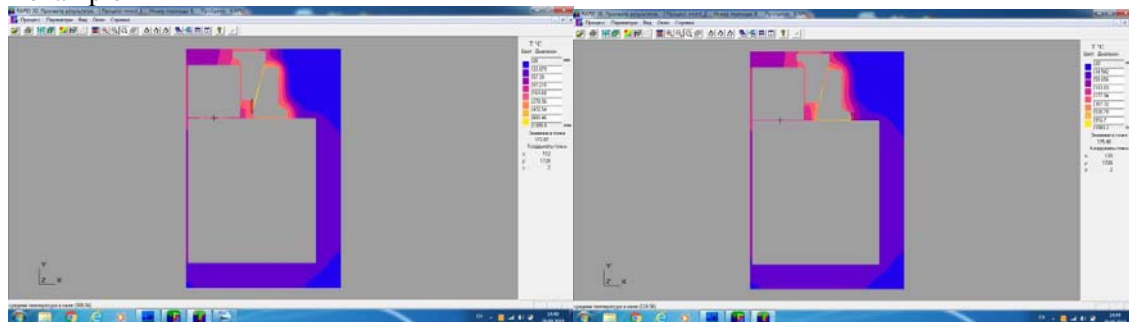


Figure 5. Average temperature decreases from 309 degrees (left; pierce point position not complying to the part hardness rule) to 120 degrees (right)

An example 2

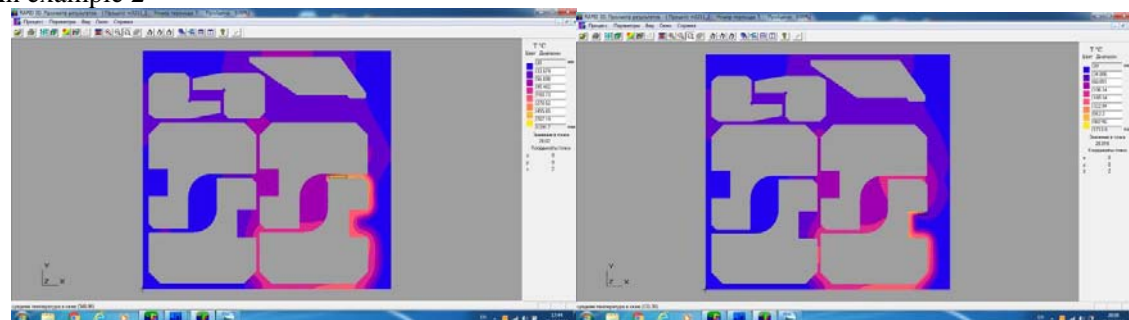


Figure 6. Temperature decrease from 550 degrees (left) to 130 degrees (right)

4. Conclusions

It has been shown that analysis of temperature fields during thermal sheet cutting on the CNC cutting machine can be used as additional consideration for tool path optimization in order to decrease thermal deformations. The results obtained are in good compliance with empirical “part hardness rule”.

Acknowledgement

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References

- [1] G Wäscher, H Haußner and H Schumann 2007 *European Journal of Operational Research* **183** (3) 1109 <https://doi.org/10.1016/j.ejor.2005.12.047>
- [2] M A Carravilla, C Ribeiro, J F Oliveira 2003 *International Transactions in Operational Research* **10** 651 <https://doi.org/10.1111/1475-3995.00434>
- [3] Hoeft J, Palekar U S 1997 *IIE Transactions* **29** (9) 719 <https://doi.org/10.1023/A:1018582320737>
- [4] Petunin A A 2009 *Ser. Upravlenie, vychislitel'naya tekhnika i informatika* **13** 280 (in Russian) <http://journal.ugatu.ac.ru/index.php/Vestnik/article/view/1144>
- [5] Petunin A, Krotov V 2015 *Mashinostroenie, Energetika* 466 (in Russian)
- [6] Chentsov P A, Petunin A A 2016 *Ifac papersonline* **49** (12) 645 <http://dx.doi.org/10.1016/j.ifacol.2016.07.762>
- [7] Petunin A A, Stylios C 2016 *IFAC-PapersOnLine* **49** (12) 23 <http://dx.doi.org/10.1016/j.ifacol.2016.07.544>
- [8] Petunin A A, Polishuk E G, Chentsov A G, Chentsov P A, Ukolov S S 2016 *AIP Conference Proceedings* **1789** 060002 <http://dx.doi.org/10.1063/1.4968494>
- [9] Glowinski R, Lions J L, Trémolières R 1967 *Analyse numérique des inéquations variationnelles. 1-2* Dunod Paris